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MAPPING THE MOON BY RADAR

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Reprinted from

DATA PROCESSING
MAGAZINE

NOVEMBER 1967

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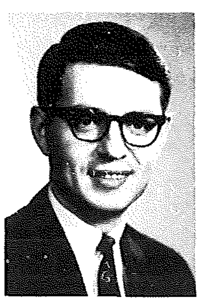

It has become increasingly apparent that the large, earth-based telescope, while still capable of providing valuable new information on our nearest celestial neighbor, has effectively fulfilled its potential for extending our basic knowledge of the moon. This does not mean that additional optical photographs of the moon are unneeded, or even that there is no new information to be gained from earlier photographs. What it does mean, however, is that entirely fresh techniques of observation are necessary if entirely fresh data is to be acquired. The technique described here involves the use of computers to collect and interpret the enormous quantities of data obtained from radar observations.

Why Radar?

The first real indication that radar probing might yield significant information on the moon came in 1946, when the United States Army Signal Corps first succeeded in bouncing a signal off the lunar surface. Even then, some of the advantages radar might have over optical methods were evident. For example, certain quantitative changes in the polarization and absorption of reflected signals resulting from transmissions at different wavelengths might give us insight into the depth, and even the nature, of the surface layer; extremely accurate determinations of range and surface features, as well as of lunar periods and possible unexpected perturbations, might be made; and perhaps of greatest eventual value since neither distance to the target nor atmospheric conditions constitute major problems, the methods developed for studying the moon could be readily adapted to planetary use.

How It Works

The method described here, usually referred to as Doppler-ranging, is an application of the same principle that explains the apparent change in the pitch of automobile horns when cars pass on the highway. The horn frequency increases as the car approaches and decreases as the car recedes.

As seen from the earth, the moon is a large disk. Because it rotates slightly back and forth on its vertical axis, half of the disk always seems to approach and half always to recede from the earth. If we divide the disk into a series of vertical strips, it is clear that those strips farthest from the center will exhibit the greatest change in echo frequency. The edgemost strip moving toward us will be of highest frequency and the edgemost strip moving away will be lowest. The intervening strips will exhibit correspondingly less change in frequency as we move our attention closer to the center. At the center strip, since there is no apparent rotational motion either toward or away from the earth, there is no rotational shift in the signal reflected from the moon.

Since 1965, the M.I.T. Lincoln Laboratory, at its Haystack facility in Tyngsboro, Massachusetts, has been conducting experiments involving the use of a microwave antenna and several computers to produce radar maps of the moon. The author has been associated with this project as a programer analyst for the past year, and unless otherwise specified, all photographs, diagrams and descriptions refer to research performed at this installation. The Haystack facility is operated with support from the U. S. National Aeronautics and Space Administration under contract NSR 22-009-106.

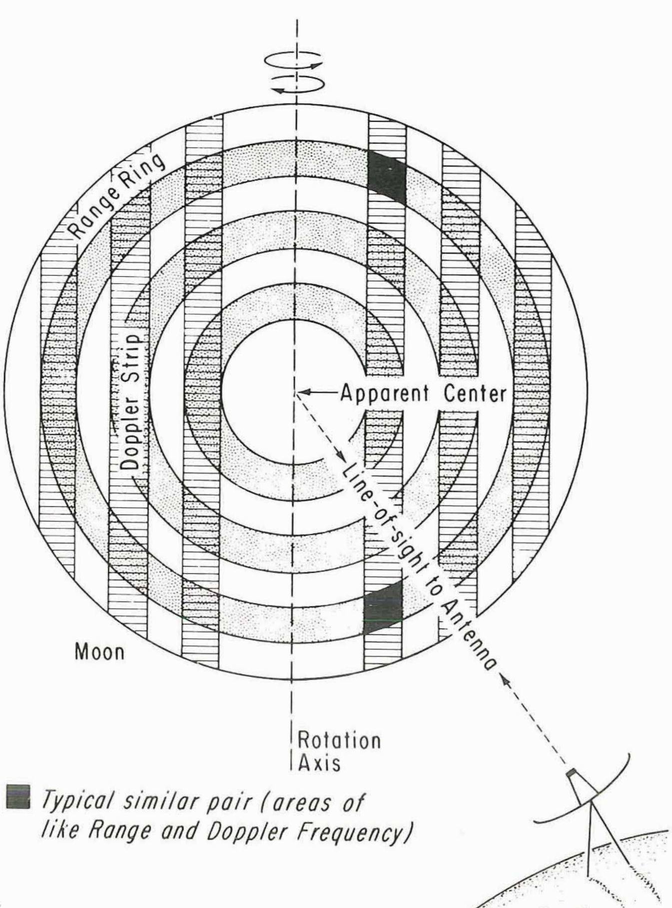

Figure 1. Radar Coordinate Plot

Since the strips yield only ordinate information, some corresponding phenomenon must be found to supply intersecting coordinate values. These values result from the fact that the moon is spheroidal, and therefore its center is closer to the earth than are its edges. Points equidistant from the earth, i.e., having the same delay time, can then be connected to form a series of concentric circles or "range rings" about the apparent center. As shown in figure 1, the resultant semipolar grid formed by the convergence of range rings at upper and lower areas on each vertical strip requires only that the beam be narrow enough to uniquely identify each of the two areas. (For planetary studies, of course, the beam cannot be held as tightly; thus it becomes necessary to code the transmitted pulses to provide such identification.)

The Computer's Role

Unlike an optical telescope, the radar antenna both emits and receives its own energy, thereby providing the observer with considerably more control of his environment. Conversely, the need for this control is proportionately greater. It is characteristic of such complex systems that the degree to which information can be obtained is as much dependent on the computer's ability to correlate data as on the primary hardware to generate it.

The central processor used for the radar system at the Haystack facility is a UNIVAC 490, operating in both real- and non-real-time modes, with a core storage of 32,000 words. Since the 490 is not the only computer tied into this project, its main task is to provide tracking input to the antenna. A Control Data 3300 is used for most of the actual processing. A complete picture of computer functions, as shown in figure 2, would include operations performed in six major areas:

1. Pre-run calcuations
2. Real-time tracking of a point on the moon's surface in both range and Doppler
3. Real-time gathering of data
4. Post-run analysis of data.
5. Correction of data and transformation of coordinate systems
6. Display of data

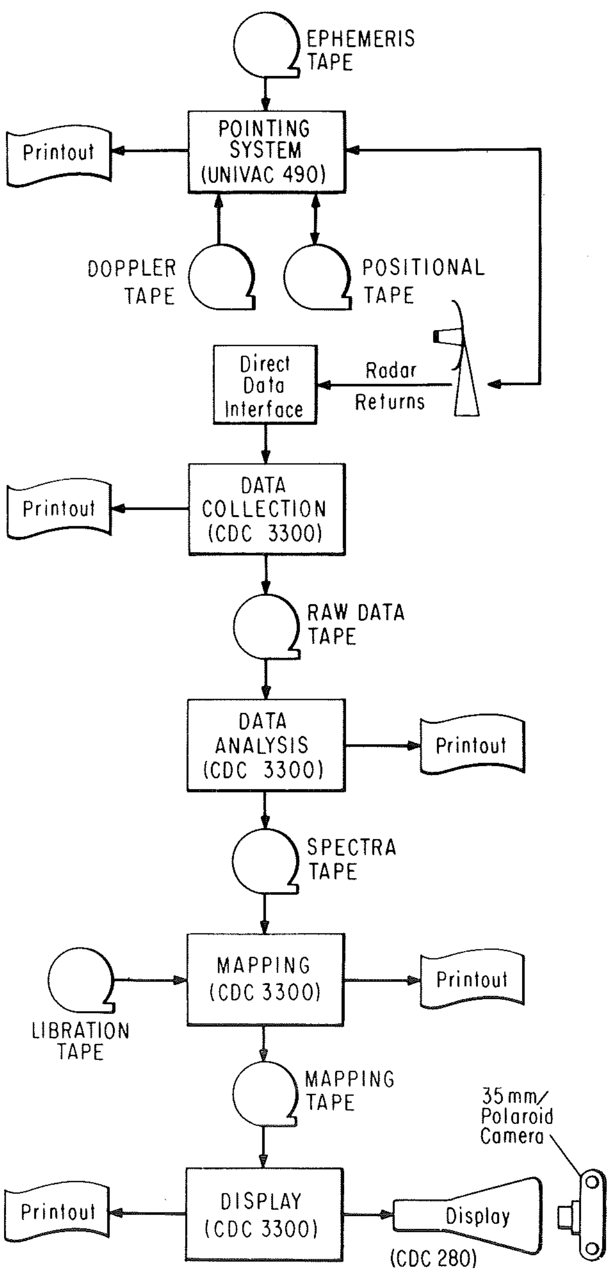

Figure 2. System Diagram for Lunar Mapping by Radar

Pre-run Calculations

The information used by the UNIVAC 490 to track the antenna is prepared from two magnetic tapes containing binary ephemeris data from the Nautical Almanac. In addition to providing lunar data, these tapes can be used to determine times and positions for the sun, five radio stars and each of the planets.

The ephemeris tapes are processed by the CDC 3300 to produce a dated run tape which is then physically transferred to one of the four tape drives on the UNIVAC 490. A printout is also produced for use by the antenna console operator and by other key personnel to periodically verify actual altitude-azimuth headings with computed headings.

A libration tape, accounting for lunar rotational motion; and a Doppler tape, to compensate for the relative motion of a point on the moon's surface, are similarly prepared before tracking. The former tape will be used by the CDC 3300 during post-run analysis, and the latter by the UNIVAC 490 to control the radar receiver during real-time tracking.

Other pre-run calculations include programs to simulate conditions for future experiments and to perform diagnostic checks on standards and equipment.

Real-time Tracking

The small beamwidth (about 3 minutes of arc at 10,000 megacycles) and great precision necessary to produce lunar pictures of optical quality require a pointing accuracy of not less than 0.005 degree (18 seconds of arc). Furthermore, this precision must be maintained for the moon's angular rate of about 0.004 degree per second.

Tracking control is provided automatically by the UNIVAC 490 as instructed by an operator at a conventional typewriter console. The operator can select any of eighteen different tracking modes or initiate a scan by simply typing the target designation. If an improper request is received by the computer, a message transmitted via the teleprinter informs the operator as to what additional information is necessary. Cor-

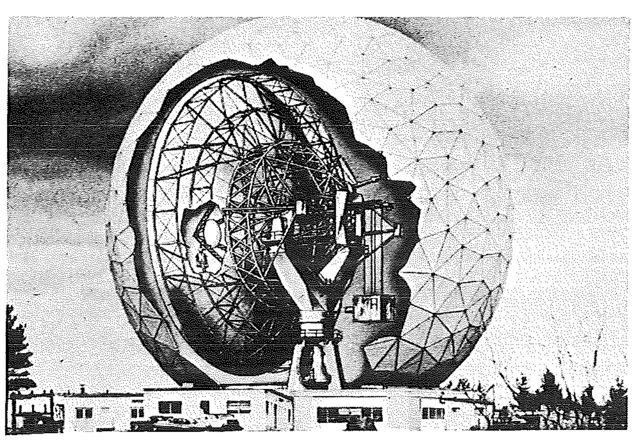

Figure 3. The Haystack Radar Antenna at M.I.T. Lincoln Laboratory.

rections or modifications may similarly be entered into the program while a scan is in progress. Extremely small angular changes are sensed and automatically entered into the program by a specially-developed digital electro-mechanical system capable of indicating angular changes of less than two-and-a-half seconds of arc.

All real-time input is computed with the run-tape data to provide the antenna servos with a new set of pointing instructions once every four milliseconds. The Haystack antenna, 120 feet in diameter, and with a suspended weight of almost 200 tons, is shown in figure 3.

Real-time Gathering of Data

The process of gathering data begins with the first transmitted pulse from the antenna. These five-microsecond pulses are sent approximately every 36 milliseconds, and a 20-millisecond "window" is provided for the study of an 800-microsecond interval within the interpulse period. Since the mean range of the moon is 3.844×10^5 meters, there is an average echo delay of 2.56 seconds before the first incoming pulse is received. Typically, a sampling run of fifteen minutes would provide sufficient data for producing about 100 sub-maps.

Not all the reflected energy received by the antenna is accepted as data. Instead, the received signal is sampled at fixed intervals. While the sampling is directly related to picture quality, its upper bound is constrained by the hardware and computer. A sampling rate of five microseconds was used to produce the left photograph of the crater Tycho in figure 4. Although its resolution of about 900 meters is roughly three times coarser than can be expected from the best optical pictures, it still compares well with the optical photograph on the right, which has a resolution of about 300 meters.

The high sampling rate and large amount of data have necessitated the construction of a direct storage interface. The raw radar data is pumped from the receiver to the interface and then into the core memory of the Control Data 3300. The data fills most of the available 32K words of storage, where it remains until read onto magnetic tape during the next transmission period.

Post-run Analysis

Spectral analyses of the data are performed in order to correlate the relative distribution of reflected energies across the observed frequency range for each intercepted range ring section. The particular Fourier program applied to the spectral analysis makes use of the Cooley-Tukey algorithm as the fastest method yet found for computing this information. Nevertheless, the computation time is approximately 45 minutes.

There are two reasons for this large amount of time. First, the size of the data makes it necessary to use a large disk file for intermediate storage. Secondly, because almost one hundred sub-maps of the same lunar region are produced during each observation run, a separate analysis must be performed for each.

The output from the spectral analysis is a set of frequency spectra which provides 256 frequency lines for each sub-map. The grid formed by the intersection of these lines with 200 associated range coordinates creates over 50,000 delay-frequency cells to which reflected power values can be assigned.

Data Correction and Coordinate Transformation

Before the hundred or so individual sub-maps can be summed to form one map, predictable variations

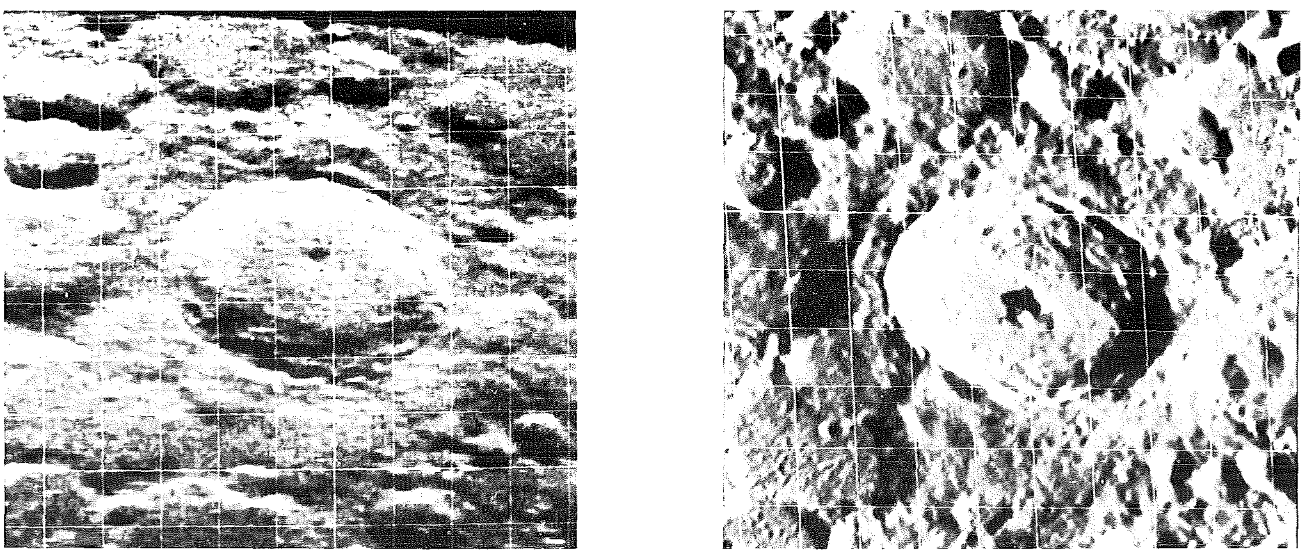

Figure 4. Radar (left) and Optical Maps of the Crater Tycho

in observed power resulting from beam shape and scattering effects have to be accounted for. These variations must be removed in order to determine local scattering efficiency, that is, the ratio of observed to predicted signal power. The statistically significant differences in power which then remain indicate differences in the lunar surface.

Scattering efficiency is computed after normalizing the data for the following factors:

1. Antenna beam shape
2. Change of scattering associated with the geometry of Doppler strips and range rings
3. Decrease in power with delay given by the mean scattering law

Other factors affecting reflected power may also be compensated for at this time. These might include changes due to the eccentricity of the moon's orbit which cause the actual range to vary by $\pm$ 8 percent of the mean range over a lunar cycle. While this would alter the echo power by $\pm$ 30 percent (approximately 1 decibel), the effect is usually too small to be significant.

After the data has been corrected, it is transformed from frequency vs. delay coordinates to selenographic latitude and longitude as shown in figure 5. Since the local scattering efficiency is a measure of the power

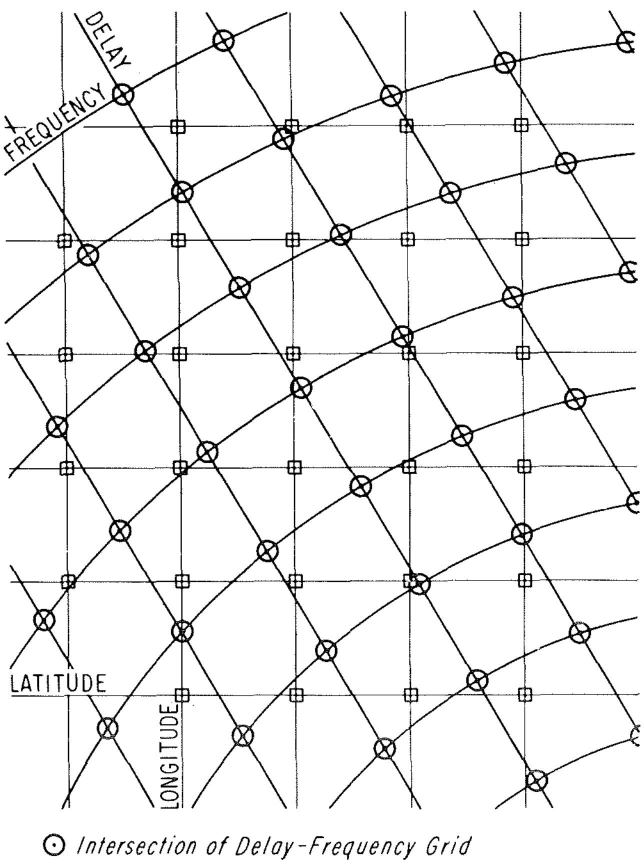

Figure 5. Delay-Frequency Mapping on Selenographic Coordinates

reflected by some finite area surrounding a delay-frequency grid point, these small areas are referred to as delay-frequency cells. The same is true for the selenographic grid points and these areas are then celled selenographic cells. Thus, the problem of transformation becomes one of transferring relative scattering efficiencies from the delay frequency grid to the selenographic grid.

Data Display

The hardware purchased for this project was chosen without any fixed idea of the nature of the final output, and therefore a general vector display processor, the Control Data Model 280, was selected. This hardware, however, has proven to be so well suited for lunar mapping that few modifications have been made to it since its acquisition. The total display configuration consists of a 19-inch monitor, a five-inch slave unit with a Polaroid film-pack camera, and another five-inch slave unit with a 35mm camera.

The first approach to mapping was to try a contour plot of the data. This involved connecting points of equal value with lines similar to the way topographic or weather maps are prepared. The only restrictions placed on these lines were that they not extend beyond the picture area or beyond other contour lines.

One of the major problems with this method was that the data used had a very great range of values, and that 90 percent of the data fell in the lower third of this range. The poor distribution of values resulted in a lack of high-intensity contour lines and a profusion of lines at the low end.

A more serious problem stemmed from the need to reject a large amount of available data. Retention of all the data would often cause the screen to appear completely white when every value in the data base was contoured. Thus, to insure space between contour lines, part of the data had to be discarded.

The next step in the development of a lunar display process was to represent the intensity of each data point by a small pattern of display points. The console was capable of displaying 1024^2 points, and at that time the total data base contained 100^2 points. A 10×10 pattern size was chosen, and after finding that only ten recognizable patterns could be generated in an area one-hundredth the size of the total picture, the data was scaled to values between one and ten.

Although providing a more satisfactory image and returning considerably more information, this method still left substantial parts of the map void of display points. These blank areas were directly attributable to the scaling, which—due to the large actual ranges (1 to 100,000) and unequal distribution of values—had assigned pattern values of less than one to many of the data points. This deficiency was corrected by a change of scaling which left the high values unaffected and adjusted the low-order values upward. By this stage of development, the pattern presentation had come to look somewhat like its optical counter-

Continued on page 32

part. Due to the apparent "busyness" of the point patterns, however, there was a certain amount of unnaturalness about it.

The next logical approach was to present each data point as a point on the display. This raised the problem of differentiating between the magnitudes of neighboring points, and was first resolved by overstriking each point as many times as would make it equivalent to its intensity. It was soon found that this was unnecessary, and that the number of overstrikes could be scaled down without noticeable loss of information. Experimentation with intensity ranges from 0-16 to 0-256 has confirmed the range 0-19 as being most consistent with desired display time and picture quality.

This technique was further enhanced by developing methods for interpolating points between those provided by the data. The radar photograph in figure 4 was produced from a data base of 200^2 data points and contains a mapping area of 1000^2 displayable points.

Together with this increase in the number of displayed points, the pattern in which they appeared on the screen was changed. Previously, the points were displayed in straight vertical and horizontal lines, such that the eye could distinguish blank rows and columns when the pictures were closely inspected. By horizontally displacing alternate rows half the distance between points, a pattern like that used to produce half-tone prints was formed, and the visual quality of the picture thereby improved.

It was also found that much of the remaining separation between points was filled by the natural diffusion of overstruck points on the film. This allowed large white areas to appear uniform in texture rather than as a series of bright points separated by dark areas. Furthermore, since the data is presented one point at a time, this additional smoothing required no corresponding increase in display time. At present, the time for producing these pictures is on the order of one-and-a-half minutes.

The Next Steps

Current efforts to increase the power and sensitivity of radar observations, to reduce processing time and enhance picture resolution, and to significantly improve microwave and data processing hardware will no doubt have major effects on the future of radar astronomy.

In the data processing area, the immediate goal is obvious: to develop tonal display systems capable of permitting the continuous display of radar data. This, together with the need for solutions to the special problems imposed by planetary observations and the constant search for better resolution, should provide enough work to keep researchers busy for a long while.

The use of the facilities of the Lincoln Laboratories Millstone/Haystack complex, provided by the U.S. Air Force, is gratefully acknowledged.